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Structural Evolution Of Part Of Northeastern Potwar Basin, Pakistan

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ABSTRACT

The Potwar Fold-and-Thrust Belt (PFTB) represents the western margin of the Himalayan Foreland Fold-and-Thrust Belt in Pakistan. This study investigates the structural evolution of a part of the northeastern PFTB through structural cross-sections constructed in 2-D and 3-D workflow, integrating the seismic section PR-92-26, structural data of surface geology, and well data from Kalar X-1. The geological formations in this region are distinguished by a wide range of rocks present at both the surface and subsurface, spanning from the Precambrian period to the Recent era. Notably, the Rawalpindi and Siwaliks groups have been exposed and are observable within the study area. The cross-sections revealed the subsurface fold geometries and kinematics of thrusts, illustrating the deformational history of the study area. The basement is identified as prominent reflector at time 4.1s or 4100ms on seismic section PR-92-26, corresponding to the depth of 9020 meters. The interpreted seismic-section demonstrate that the folded and faulted structures present in the subsurface formed as a result of back thrust and blind thrusts underlying these structures. The structural style in the northeastern PFTB is influenced by detachment folding and fault-propagation folding. A 3-D structural model was created to better understand the subsurface structural geometry, variations, and terminations of structures across the section lines. The model suggests that the regional structures extend to a depth of 9 km in the subsurface. The two deformed and restored cross-sections (AA/ and BB/) indicate that the sedimentary cover experienced approximately 29% or 6 km of shortening due to deformation.

Keywords: Structural Kinematics, 2-D & 3-D Structural Model, Seismic Interpretation, Northeastern Potwar Basin, Crustal Shortening.

INTRODUCTION

The Potwar Fold-and-Thrust Belt (PFTB) is an active Himalayan foreland basin located at the northwestern margin of the Indian Plate that formed as a result of the ongoing collision between the Indian and Eurasian plates in northern Pakistan (Tariq Majeed Jaswal, 1997). It has experienced several deformation phases during Himalayan orogeny in Pliocene to Middle-Pleistocene, as identified in the stratigraphic profile of the basin i.e., regional unconformities which serve as compelling evidence of severe tectonic episodes (Pennock, 1988). Tectonically, the PFTB can be divided into three tectonic zones: western, central, and eastern, each exhibiting a distinct style of deformation. The western and central regions experienced deformation caused by left-lateral strike-slip movement along the Kalabagh Fault and north-dipping thrusting along the Salt Range Thrust, respectively. In the eastern part, the rocks trend northeast-southwest and were subjected to a broader zone of deformation. This zone features broader synclines separated by tight to overturned anticlines, associated with thrust faults. (Grelaud et al., 2002). In terms of sediments influx, the PFTB has a diverse sedimentary record, including a thick sequence of Infra-Cambrian evaporites, a relatively thin layer of calcareous-siliciclastic rocks of the Indian Plate ranging from Cambrian to Eocene, and very thick molasse deposits of the Indus Foredeep that date back to the Miocene-Pliocene epochs, indicating a substantial sediment influx (Grelaud et al., 2002; Tariq Majeed Jaswal, 1997).

Several geoscientists have conducted significant research on subsurface structures in the eastern Potwar Fold-and-Thrust Belt. Notable examples of such research include studies by Butler et al. (1987), Leathers (1987), Dan M. Baker et al. (1988), Jaumé and Lillie (1988), Pennock (1988), Pennock et al. (1989), Jaswal et al. (1997), Kazmi and Jan (1997), Grelaud et al. (2002), Aamir et al. (2005), Aamir and Siddiqui (2006), Shahzad et al. (2008), Barry et al. (2013), Jadoon et al. (2015), Abbas et al. (2019), Mehmood et al. (2021) and Yasin et al. (2021). Structural interpretations and the detailed timing of events were determined by Burbank et al. (1986) and Butler et al. (1987); Johnson et al. (1986), while Butler et al. (1987) and Leathers (1987), as well as Hasany and Saleem (2012) and Iqbal et al. (2015), focused on the structural kinematics of the Potwar Plateau. However, a 3D structural model of the northeastern PFTB to validate the subsurface structural geometry is currently lacking.

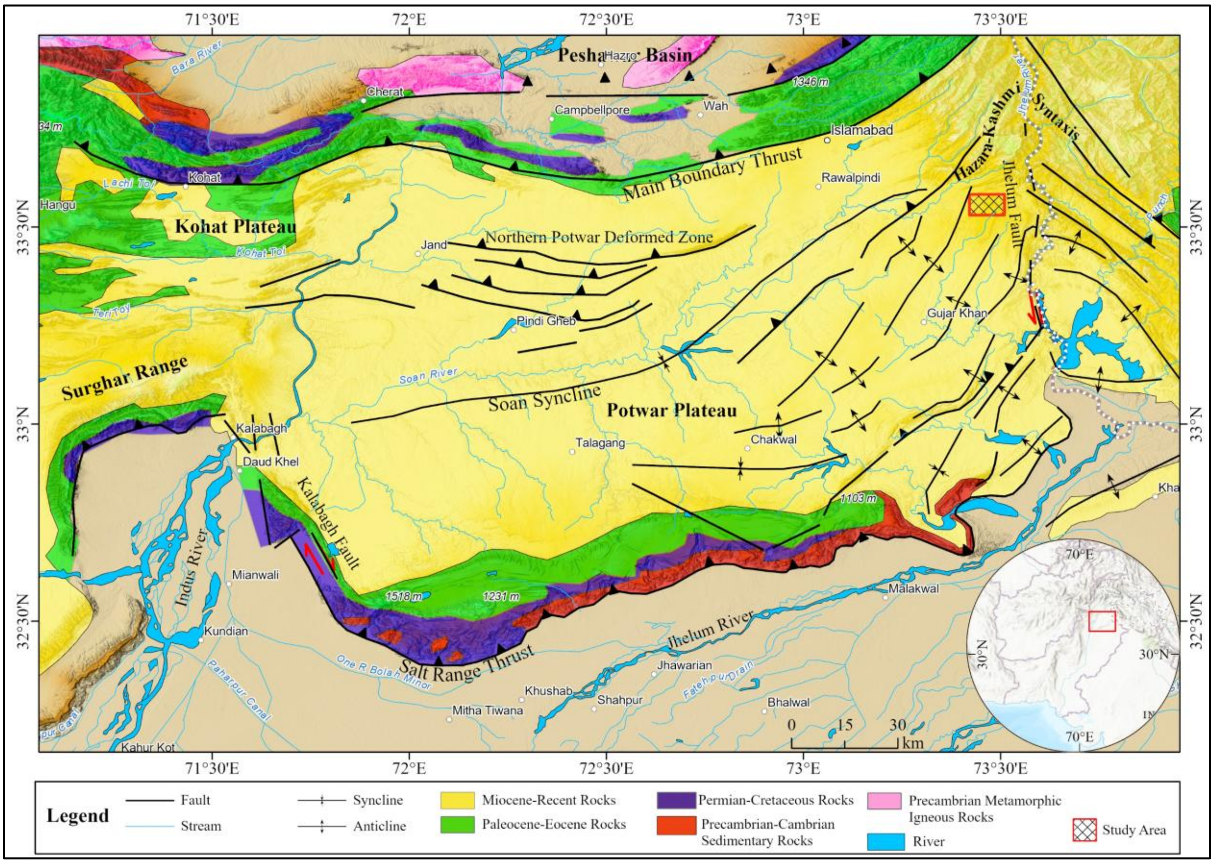

Fig. 1: The location of study area is *shown* by a rectangular box on *a digital elevation model background*, highlighting the geological structures of the Potwar Basin, as adopted from M. A. Khan (1986).

To fill this gap, the present research work focuses on creating a 3-D structural model of the northeastern PFTB around the Kalar Syedan and Kahuta areas to understand its structural evolution and calculate the total amount of shortening accommodated by the structures using restored cross-sections. The study area is bounded by the Margalla Hills ranges to the north, the Indus River and Kohat Plateau to the west, and the Jhelum River and Hazara-Kashmir Syntaxis to the east, as depicted in Figure 1. This work provides valuable insights into the Himalayan foreland fold-and-thrust belt, offering detailed information on the topographic and basement slopes, as well as the timing of events.

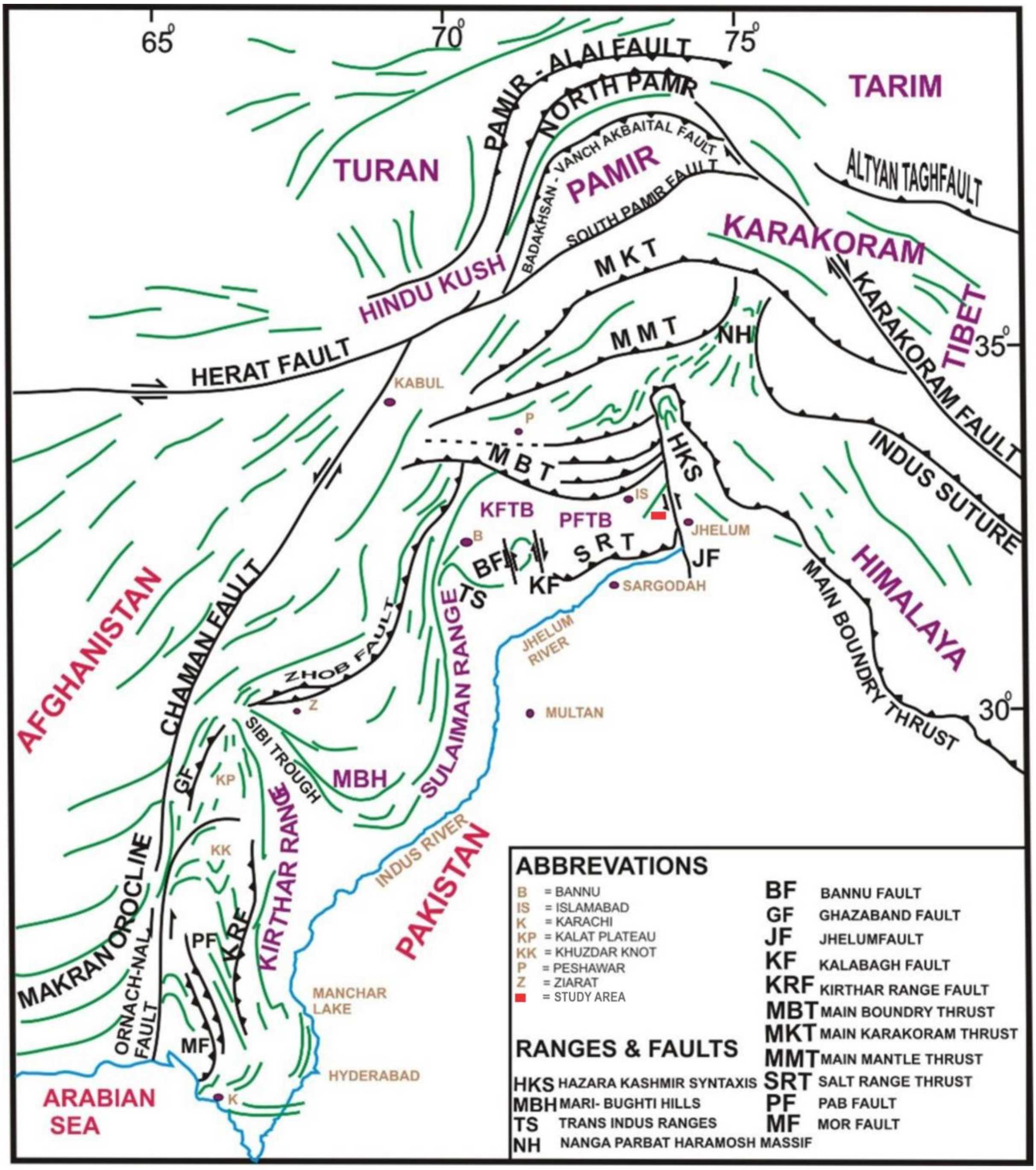

Fig. 2: A map of the north-western region of the Indo-Pakistan sub-continent illustrates the major tectonic trends and highlights the location of study area with a red box, modified after (Sarwar & DeJong, 1979)

1. Tectonic Setting and Stratigraphy

The boundary of the Indian Plate in northern India and Pakistan experienced a collision between the Indian and Eurasian plates during the Eocene, leading to the formationof the Himalayas (Greco & Spencer, 1993; Spencer, 1993). The primary structural and stratigraphic setting of the Indian plate has been significantly influenced by plate movements that occurred from the Late Paleozoic to the present. The northwestern part of the Himalayas are divided into litho-tectonic domains characterized by distinct geological and physiographical features (Sarwar, 1979) (Fig. 2).

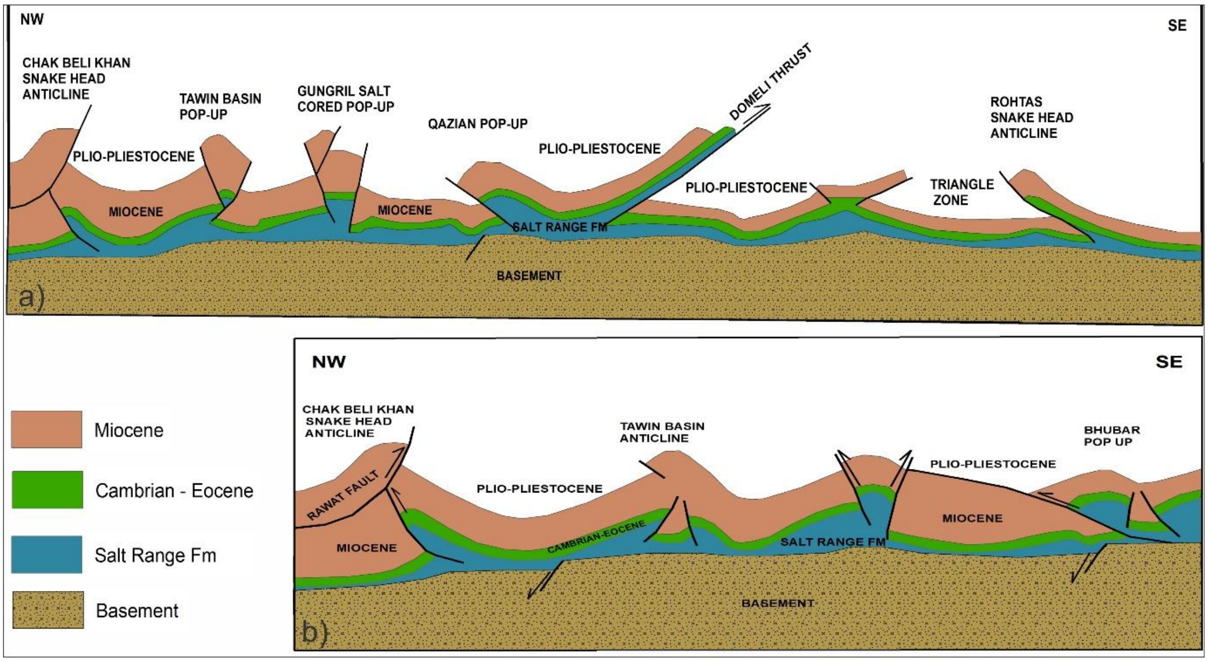

Fig. 3: Balanced cross-sections of the central/eastern Potwar sub-basin, as presented by Moghal et al. (2007). Panel (a) illustrates the Chak Beli Khan, Tanwin-Bains, Gungri-Qazian, Mahesian, and Rothas structures. Panel (b) depicts the Chak Beli Khan, Tanwin-Bains, Adhi, and Bhubar structures, providing insights into the structural evolution of the region.

The regional fault system in northern areas of Pakistan comprises four major thrust faults: the Main Karakorum Thrust (MKT), Main Mantle Thrust (MMT), Main Boundary Thrust (MBT) & Salt Range Thrust (SRT). These faults are extensive in both length and crustal shortening. If we move toward the south from the northern side of the mountainous area, these faults divide the Pakistani Himalayas into the following geological divisions (Ahmad et al., 2004):

a) Sandwiched block between Eurasia and Indian Plate, Kohistan Island Arc (KIA).
b) Metamorphosed rocks of Northern Deformed Fold-and-Thrust Belt (NDFTB).
c) Sedimentary and metasedimentary succession of Southern Deformed Fold-and-Thrust Belt (SDFTB).
d) The mountainous foothill, Punjab Foredeep.

The research area is located in the northeastern section of the PFTB, which is part of the NDFTB. The PFTB is oriented in an east-west direction and contains a thick sequence of fluvial molasse sediments. The PFTB is relatively less deformed and approximately 150 km wide in the north-south direction (Kazmi, 1979; Kazmi & Jan, 1997; Kazmi & Rana, 1982). The SRT forms its southern boundary, while the MBT marks the northern boundary along the Margalla/Kala-Chitta ranges. The PFTB is divided into two zones: the Northern Potwar Deformed Zone (NPDZ) and the South Potwar Platform Zone (SPPZ), with the boundary between them marked by the Soan Syncline. The majority of deformation is concentrated in the NPDZ, where basement rocks dip at a lower angle (1º–1.5º) in the eastern part compared to the central part, where the dip angle is 2º–3º (D. M. Baker et al., 1988; Leathers, 1987; Moghal et al., 2007) (Fig. 3).

The Eastern Potwar basin is primarily characterized by sedimentary rocks of continental origin. These sediments were deposited in a subsiding basin located on the southern flanks of the rising Himalayas (Pennock, 1988). The rocks present in the study area are of sedimentary origin, with ages ranging from Miocene to Recent epoch. Exploration history for hydrocarbons and seismic data from the study area suggest that the Salt Range Formation is the oldest unexposed rock (Moghal et al., 2007). To better understand the geology of the area, a stratigraphic column was created using data collected from surface measurements and well bores. The thicknesses of different formations were incorporated into the construction of cross-sections to provide a more accurate representation of the subsurface geology in the region. Figure 4 provides a visual representation of this stratigraphic column.

The geological formations in the study area offer valuable insights into the region's geological history. The lithology of the Murree Formation suggests that during the early Miocene, the area experienced a mix of brackish and fluviatile environments, with the fluviatile condition becoming more dominant during the early to middle Miocene, as evidenced by the prevalence of sandstone in the Kamlial Formation. The Siwalik Group formations, including Chinji, Nagri, and Dhok Pathan, are primarily composed of sandstone and clay, reflecting the accumulation of floodplain deposits during the late Miocene to middle Pliocene epoch. The presence of conglomerates, subordinate to interbeds of sandstone, siltstone, claystone, and boulders from older deposits, indicates freshwater conditions that prevailed during the upper Pliocene (Pennock, 1988). Unconformities are observed between the Dhok Pathan, Soan Formations, and Terrace gravel deposits. The Quaternary deposits of sand, silt, clay, and alluvium predominnatly cap the bedrock.

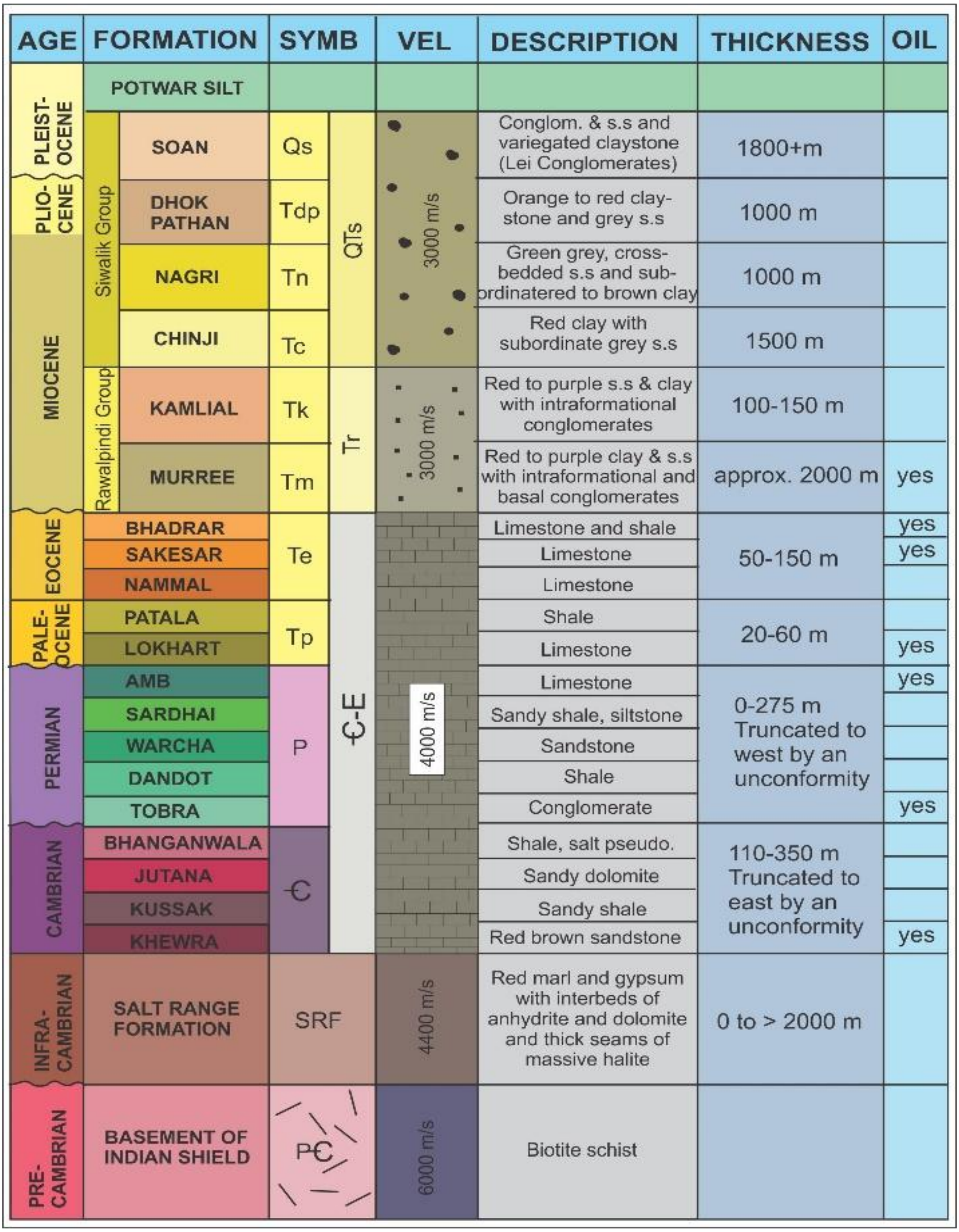

Fig. 4: Generalized stratigraphy of Eastern Potwar Basin (after Pennock et al., 1988).

2. Methodology

The present study utilized several methodologies, including reconnaissance and traverse selection, field data collection, construction of surface geological maps, interpretation of seismic data, and 2D & 3D structural modeling. In addition, the research methodology involved calculating the total amount of crustal shortening in the study area.

The geological map of the study area was created in ArcMap 10.1 software by combining fieldwork, published maps from the Geological Survey of Pakistan, and satellite image analysis to identify the geology and structure of the area. Seismic data from section PR-92-26 and well tops from Kalar X-1 were used to interpret subsurface structures and stratigraphy. Cross- sections were constructed to a depth of 9 km using seismic, well, and structural data. Section line AA/ was created along seismic line PR-92-26, while section BB/ was constructed across the surface structural trend. The seismic line PR-92-26 was used exclusively to interpret subsurface structures and determine the depth of the basement. The basement reflector was identified as a prominent reflector at 4.1s on PR-92-26, referenced to the shot point's surface location. Its character was traced throughout the section, and time values were picked accordingly. A time section for the basement reflector was prepared and converted into a depth section. The corresponding depth values were incorporated into the structural cross-section AA/ under the shot point's surface location.

The interpretation of subsurface structures was based on seismic section PW-15, which was used as a reference for marking faults on the seismic section PR-92-26. Surface faults were also marked on the seismic section in relation to the shot points. Cross sections AA/ and BB/ were restored to the basement, and the amount of shortening was calculated for the overlying sequence. The time-to-depth conversion of the basement reflector was accomplished by picking time values from different reflectors in the seismic section and plotting the corresponding velocities at different shot points in MS Excel. The depth of the reflector was then calculated using the formula:

$$\text{Depth} = \text{Time} * \text{Velocity}/2$$

To determine the amount of shortening experienced by the rocks in the study area, the cross-sections along lines A-A' and B-B' were restored to their undeformed state up to the basement using Move suite 2015.1 software. The average length of the undeformed lines (L) for both cross-sections was determined using the following formula:

$$L=A/T$$

The total deformed area (A) for Murree and Kamlial formations was measured from the restored cross-section. The regional undeformed thickness (T) of these formations was obtained from regional studies (Edward S. Pennock, 1989; Pennock, 1988; Tariq Majeed Jaswal, 1997).

The 3D structural model of the study area was created by integrating surface data and subsurface cross-section in Move™ suite 2015.1 software to demonstrate the subsurface structural geometry. The model was used toanalyze the kinematics of folds and thrusts in the study area, constructed along the lines A-A' and B-B' using field data, a geological map, and structural cross-sections. The model depicts the extension of regional structures to a depth of 9 km below the surface and their correlation with surface data. it illustrates the deformation style, variation, and termination of structures across lines A-A' and B-B'.

The 3D model was created by generating 3D surfaces of the main faults and folds in the study area. A 3D fault model was constructed by connecting fault planes established in the cross-sections A-A' and B-B'. Additionally, a 3D horizon model was created to analyze the kinematics of folds along and between the lines A-A' and B-B'. The model was used to interpret the horizons cut by faults at the level of the Murree Formation, and their current geometry between lines A-A' and B-B'. It provides a detailed view of the closure and orientation of folds in the study area.

3. Results

4.1 Structural Analysis

The geological structures in the study area are predominantly shaped by thrust tectonics, which have resulted in extensive folding and faulting. The subsurface is characterized by imbricated thrust faults and back thrusts that uplift and bisect the structures at the surface. At the surface, the geological formations exhibit broad asymmetrical synclines and tight anticlines, reflecting the compressional forces generated by the collision between the Indian and Eurasian plates.

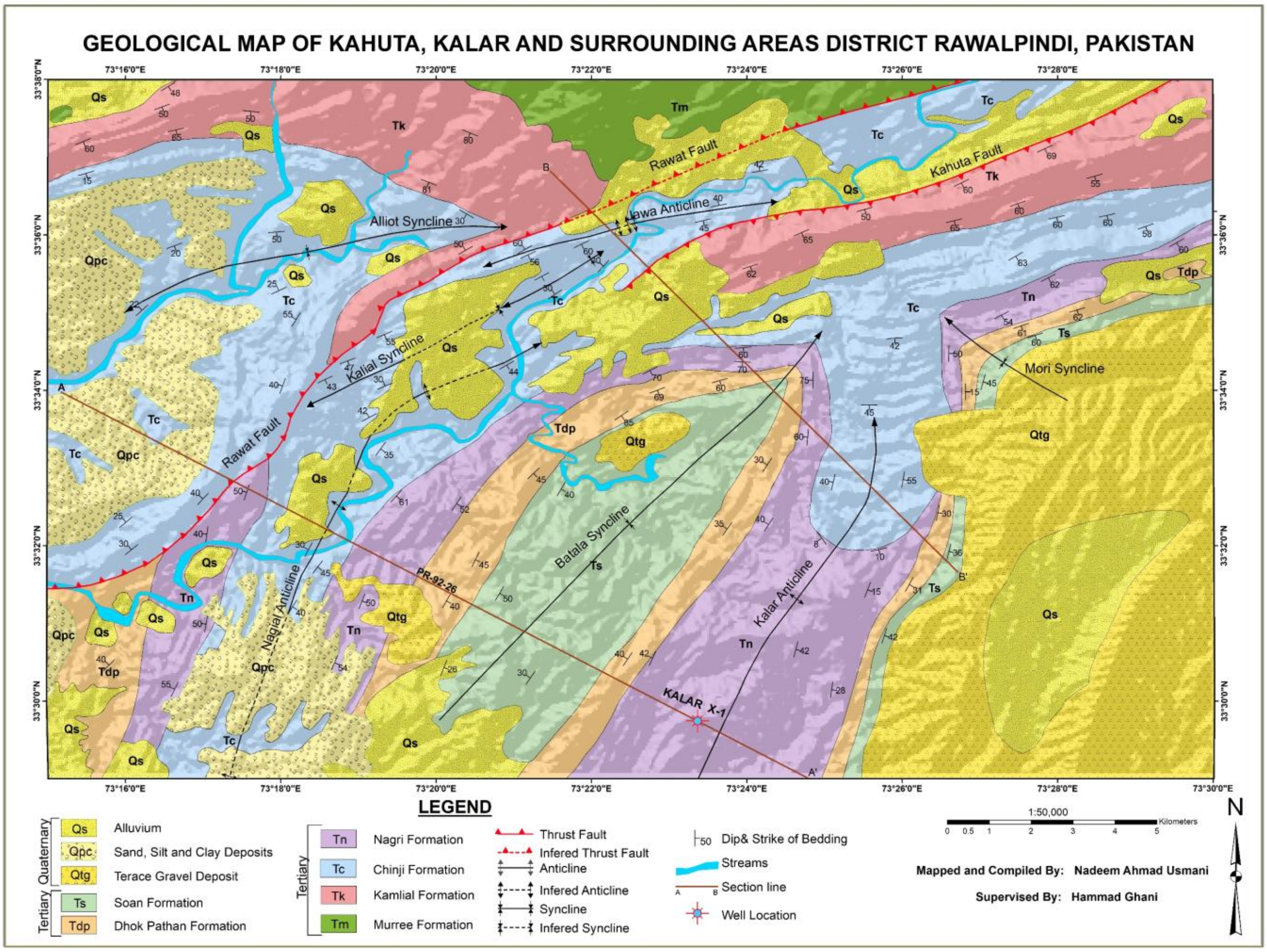

Fig. 5: The geological map of study area showing major structural elements.

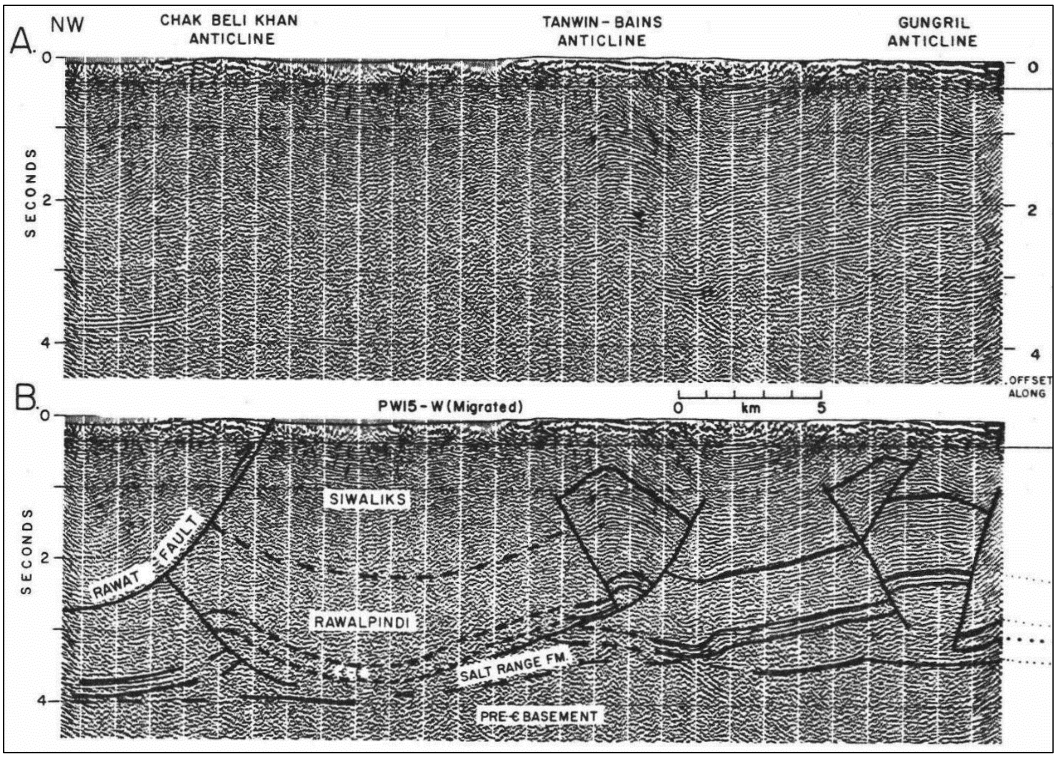

Fig. 6: In (A), an uninterpreted seismic line, PW15, is shown as it crosses a section of the Eastern Salt Range/Potwar Plateau. In (B), the portion of PW15 utilized by Pennock (1988) for a balanced cross-section is interpreted.

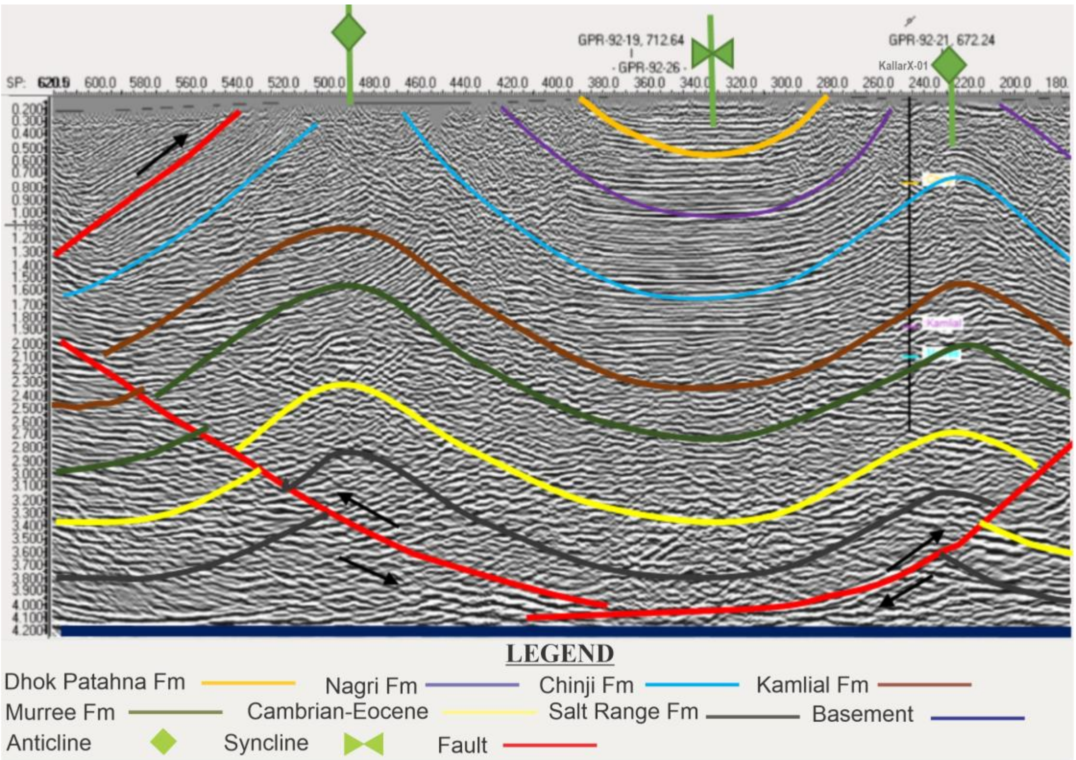

Fig. 7: Interpreted seismic section PR-92-26 across the study area.

Rawat Fault and Kahuta Fault are the major faults observed in the study area, as shown in Figure 5. Rawat Fault is characterized by northeast-southwest trending, northwest dipping thrust fault and reverse fault. On the other hand, Kahuta Fault is a southeast-dipping reverse fault with a similar northeast-southwest trend. The study area also features several major folds, including the Kalar Anticline, Nagial Anticline, Jawa Antiform, Batala Syncline, Alliot Syncline, Mori Syncline, and Mori syncline (Fig. 5). These folds range from open to tight in their geometry and play a significant role in shaping the geomorphic features of the study area, with broad synclines giving rise to valleys and tight anticlines forming ridges. The limbs of these folds are intersected by thrust faults at the surface, whereas blind thrusts cut the limbs beneath the subsurface.

4.1.1 Cross Sections

To analyze the surface and subsurface structural geometries and their transitional styles along the trend, two cross-sections were created along the lines AA/ and BB/, as shown in Figure 5. The basement reflector was identified at the shot points 620, corresponding to a time 4.1 seconds (4100 milliseconds), and its depth was calculated to be 9020 meters. This depth was used to construct the balanced structural cross-section.

The AA/ cross-section spans 17 km in the southwestern part of the study area and is oriented WNW-ESE (Fig. 5). This cross-section was constructed along the seismic line PR-92-26, with well Kalar X-1 located on it. Upon analyzing the interpreted regional section PW-15, a detailed understanding of the subsurface structural configuration was obtained. This included the extension of the Rawat fault and blind thrust in the subsurface, which played a critical role in the development of complex structures above them (Fig. 6). The structural style of the AA/ cross section was derived based on this analysis, providing a clear insight into the geometry and kinematics of the structures present in the study area. This section intersects the major structure, including Kalar Anticline in the ESE, characterized by the Nagri Formation in its core and the Dhok Pathan Formation on its limbs. In theWNW, the Rawat fault and Nagial anticline are prominent features (Fig. 7 & 8). The Rawat fault, a major thrust fault extending across the study area, is responsible for the uplift of the Siwalik and Rawalpindi Group sediments. The Nagial anticline, a relatively minor structural feature,associated with the Rawat fault, exposes Chinji formation in its core and Nagri formation on its limbs.

The Kalar X-1 well, drilled on the northwestern limb of the Kalar Anticline, revealed an anomalous thickness of the Murree Formation. The Batala Syncline, an open synclinal fold to the west of the Kalar Anticline, has the Soan Formation in its core and the Nagri and Dhok Pathan formations on its limbs. The subsurface structural style analyzed from this section indicates that the Rawat Fault originated from a basal detachment and is a high-angle thrust fault cutting through the limb of the Nagial Anticlinein its footwall block.Progressive deformation uplifted and folded overlying structures through back thrusts and blind thrusts in the subsurface (Fig. 8).

The BB/ cross-section, approximately 12.5 km long, is oriented NW-SE, and is located northeast of the AA/ section. It was constructed using surface attitude data to examine the structural variations in the study area (Figs. 5). The major structures along this section include the Rawat Fault, Jawa Antiform, Kahuta Fault, Batala Syncline, and Kalar Anticline. The Kalar Anticline, located to the southeast of the section, has Chinji Formation in the core, with Nagri, Dhok Pathan, and Soan formations at the limbs. The Batala Syncline, to the west of the Kalar Anticline, features the Soan Formation in the core, flanked by the Chinji, Nagri, and Dhok Pathan formations on its limbs. The Jawa Antiform, situated in the footwall of the Kahuta Fault, has both limbs transected by thrust faults. The Rawat Fault cuts the northwestern limb of the Jawa Antiform, while its southeastern limb is intersected by the Kahuta Fault. The Rawat Fault dips steeply at the surfacein this section, while the Kahuta Fault, a high-angle back thrust fault, originates from a blind thrust in the subsurface. It cuts upward through the Kalar Anticline and Batala Syncline to the north in the subsurface (Fig. 9).

4.1.2. Cross Section Restoration

The actual length of cross-section A-A' is 17 km, which increases to approximately 23.5 km after restoration along the folds and faults (Fig. 8). The total amount of shortening along section A-A' is approximately 6.5 km, corresponding to a shortening percentage of 27.6%. Similarly, cross-section B-B' has an actual length of 12.5 km, which increases to approximately 18 km after restoration. The total shortening along section B-B' is approximately 5.5 km, resulting in a shortening percentage of 30.5% (Fig. 9). On average, the deformational structures in the study area, as represented by sections A-A' and B-B', accommodated a shortening percentage of 29%.

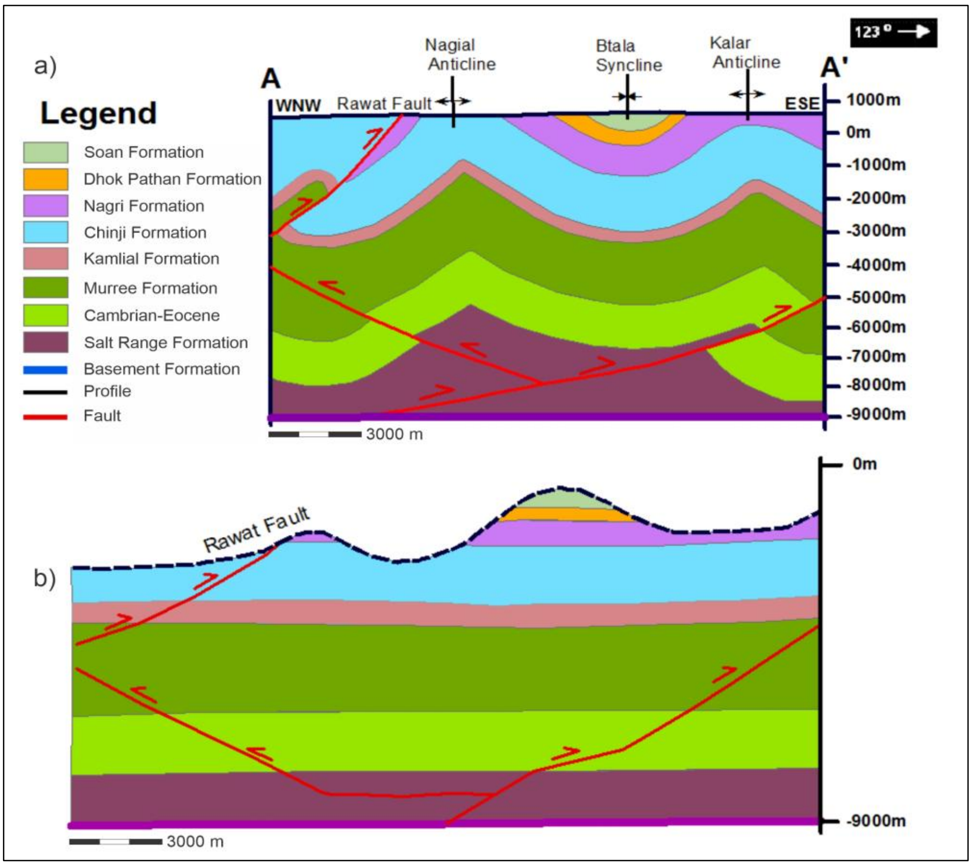

Fig. 8: a) Structural cross-section along line A-A´. b) Restored section along line A-A´ of Fig. 5.

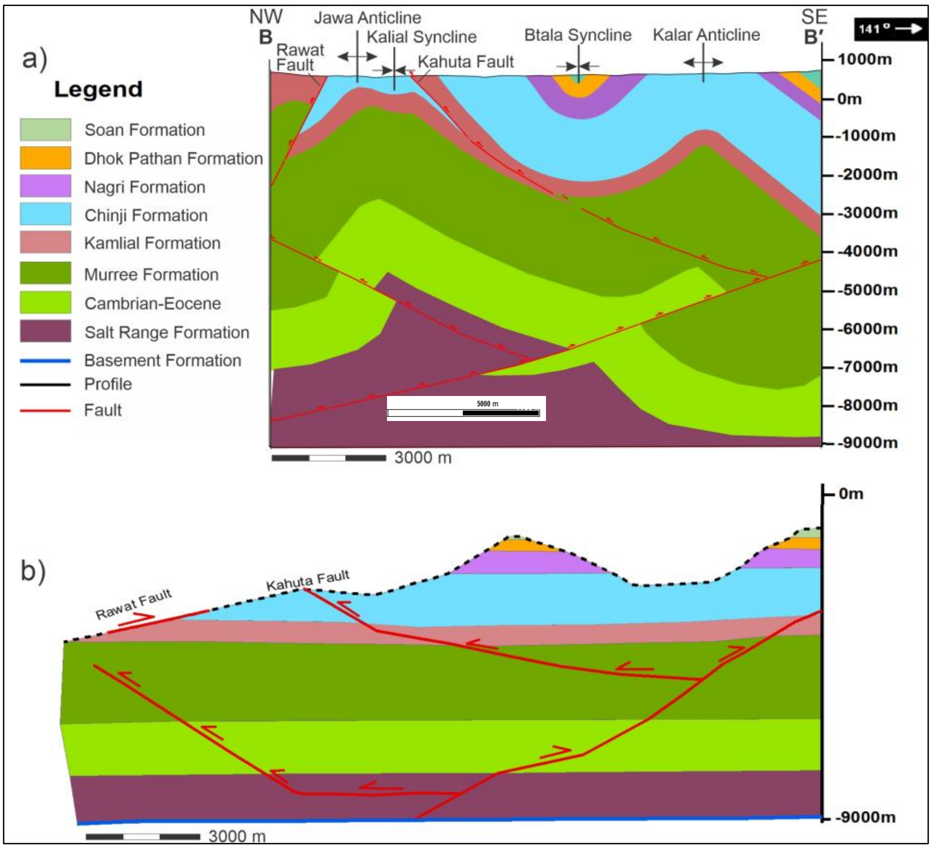

Fig. 9: a) Structural cross-section along line B-B´. b) Restored section along line B-B´ of Fig. 5.

4.1.3. 3-D Fault Modeling

Both cross-sections show the Rawat Fault as a regional thrust (Fig. 10 & 11). These faults are listric, with some exhibiting north or south verging fore and back thrusts originating from a basal detachment (Fig. 11; Fig. 12). Among the four faults observed, two are blind, while the other two are exposed at the surface. The 3D model of these faults demonstrates a trend that varies from east to west in the orientation of fault planes. While the Kahuta Back Thrust and Rawat Fault are visible at the surface along cross-section B-B', only the Rawat Fault is exposed at the surface along line A-A´ (Fig. 11; Fig. 12). The deformation and displacement of strata along the surface-visible faults indicate greater vertical displacement towards the northwest and lesser towards the southeast within the study area.

4.1.5. 3-D Horizon Modeling

The 3D model, shown in Figure 13, illustrate that the folds trend northeast-southwest and plunge towards the northeast.

4. Discussion

The PFTB is located at the western edge of the sub-Himalayas and has undergone significant deformation due to the Eocene collision between the Indian and Eurasian plates. The PFTB preserves sedimentary strata and continental molasse sequence as a result of the Himalayan orogeny. The numerous structures in the region reflect the extensive deformation of the Potwar Basin/Plateau, revealing an intense structural style.

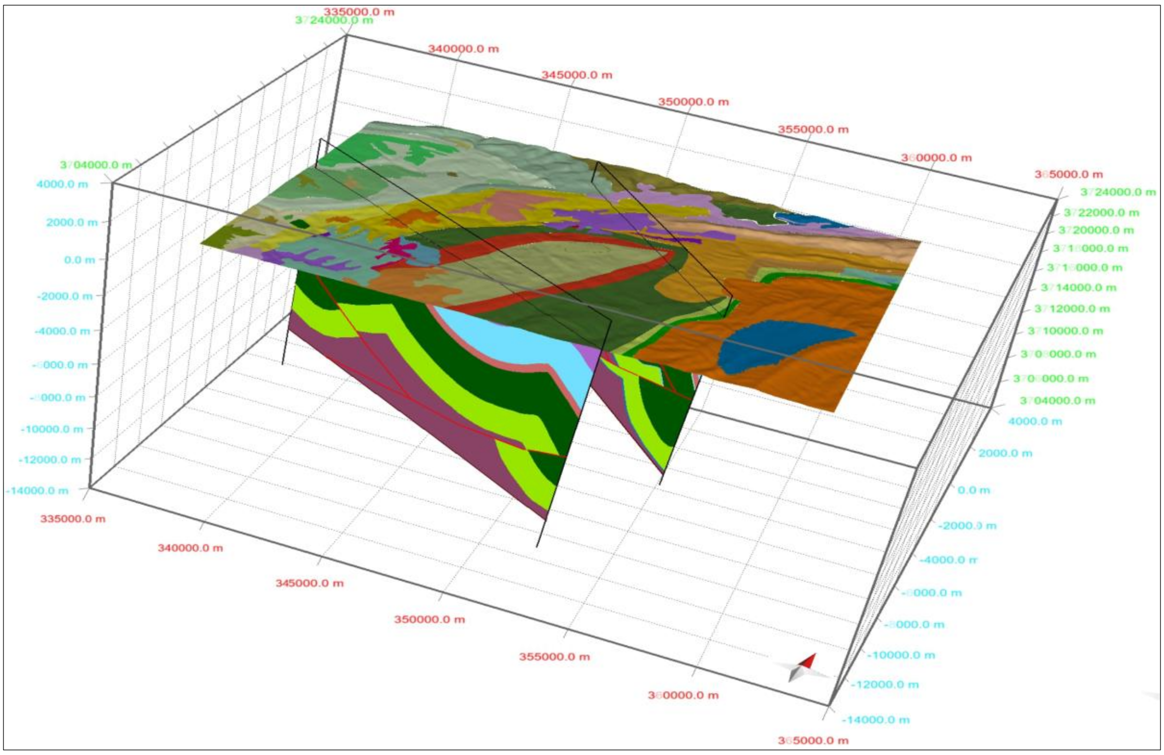

Fig. 10: The 3-D model illustrates the interaction between surface geology and structural cross-sections in the study area.

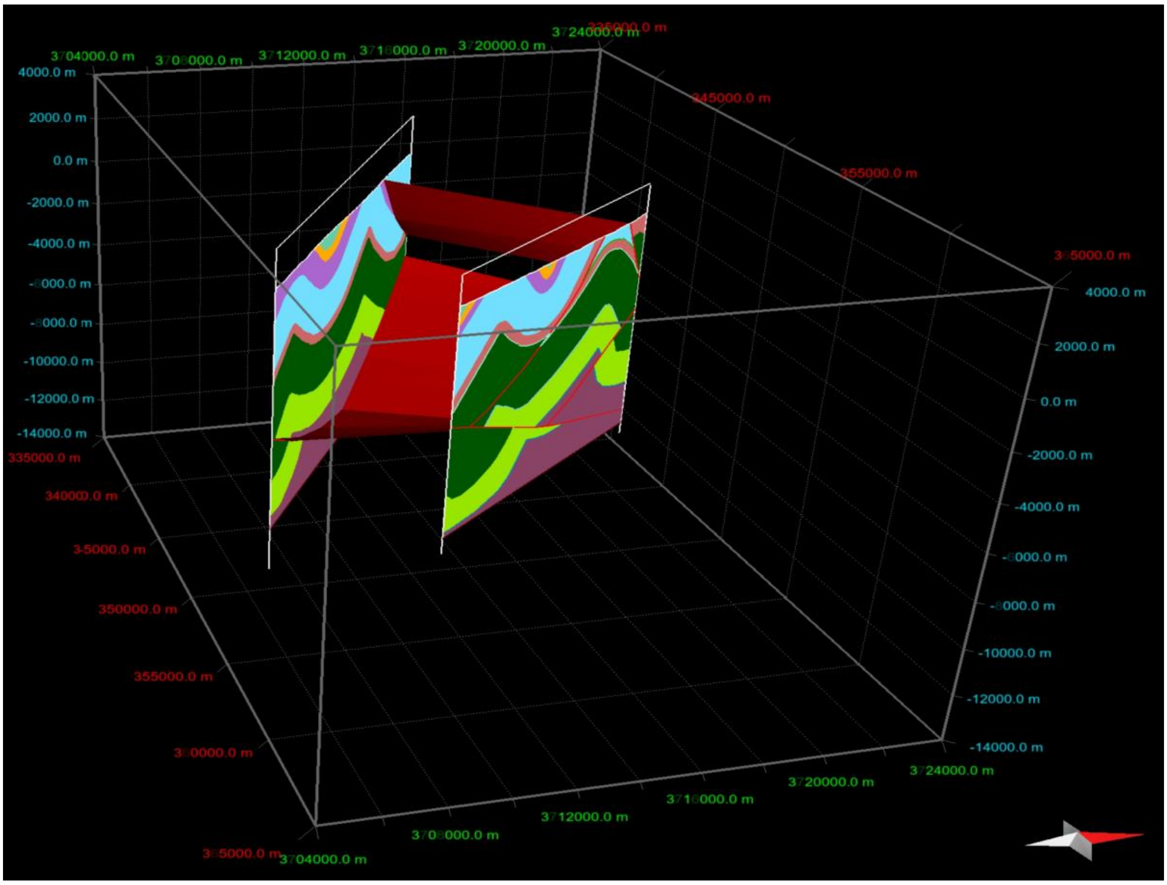

Fig. 11: The 3-D model showing the structural cross-sections across the lines A-A´ and B - B´.

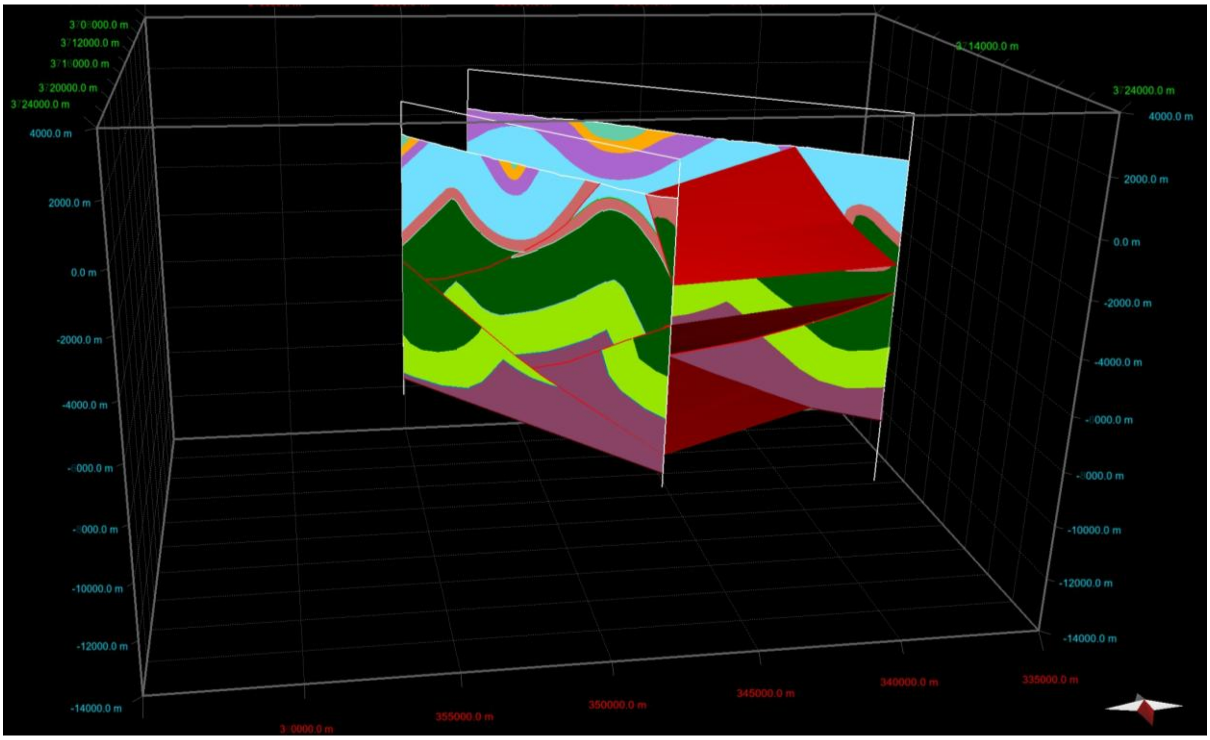

Fig. 12: A 3-D fault model of the study area demonstrates a regional thrust system.

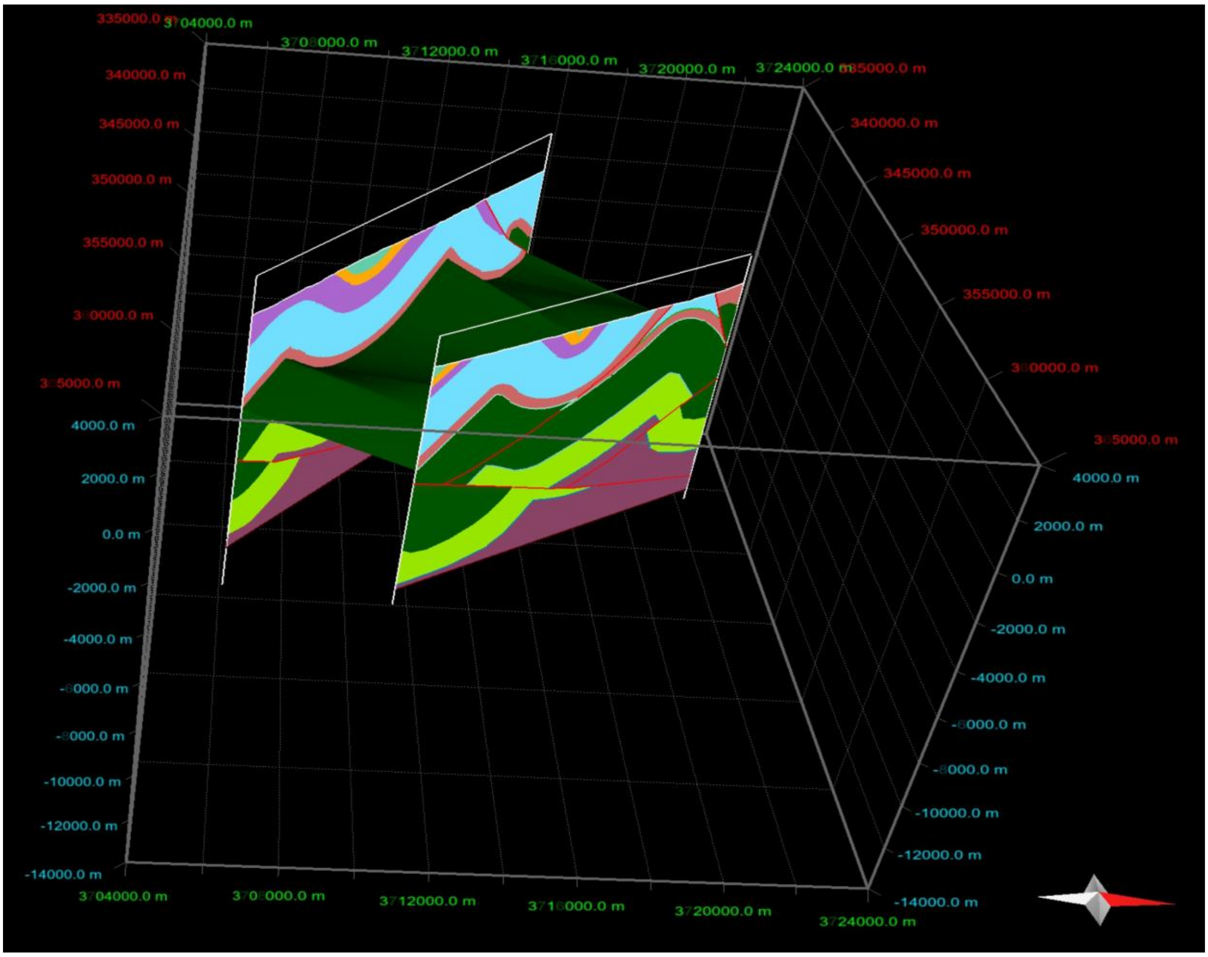

Fig. 13: The 3-D model depicts the horizon at the Murree Formation level, intersected by faults.

The aim of this study is to understand the structural geometry of both surface and subsurface structural features in the area, and to develop a comprehensive model of the region's structural evolution. This is achieved by utilizing surface geology, seismic studies, and well bore data. The main objectives of the research are to conduct 2D and 3D modeling of the study area, determine the nature of the tectonics that have contributed to the area's structuration, and calculate the amount of shortening accommodated by the structures using restored balance cross-sections. The study area contains sedimentary rocks of varying ages, ranging from Miocene to Recent, including the Murree, Kamlial, Chinji, Nagri, Dhok Pathan, and Soan formations. Unconformities exist between the Dhok Pathan Formation, Soan Formation, and Terrace gravel deposits. Quaternary deposits, composed primarily of sand, silt, clay, and alluvium, typically cap the bedrock.

Structurally, the study area exhibits intense folding and faulting, controlled primarily by thrust tectonics. Imbricated thrust faults and back thrust in the subsurface bisect and elevate the surface structures. The study area contains two main faults, namely the Rawat Fault and Kahuta Fault, which have a northeast-southwest trend and are of thrust and reverse types. The Rawat Fault formed by the Murree and Kamlial formations being thrust over the Chinji Formation, while the Kahuta Fault involves the Kamlial Formation being thrust over the Chinji Formation. These faults were identified in the field based on stratigraphy, slickensides, drag folds, shearing, and crushing. folds in the study region trend northeast-southwest, and range from open to tight. The synclines are broad and wide, creating valleys, while the anticlines, which forms ridges, are generally close to tight. The surface folds exhibit faulted limb, , while in the subsurface, these folds are core-faulted by blind thrust faults, resulting in the complex deformational style.

The cross-sections demonstrate that back thrust and blind thrusts in the subsurface are the primary cause of uplifting and folding of the overlying structures. By restoring the cross-sections to their undeformed state up to the basement, the average amount and percentage of shortening were calculated to be approximately 6 km and 29% respectively. A 3D model was developed using MOVE suite 2015.1 to better understand the structural geometries of the study area. The 3D surfaces of main faults and folds highlights thrust tectonics in the area and shows the northeast-southwest oriented plunging folds.

5. Conclusions

Based on the detailed structural analysis in the area, it has been concluded that only detachment folding and thrust tectonics are responsible for the structural evolution of the northeastern PFTB. The study area is characterized by open to tight and plunging folds that trend northeast-southwest. The amount of displacement along the faults varies laterally, and the subsurface blind thrust faults have significantly uplifted and folded the rocks. The structural variations along the strike are influenced by the variable throw of the thrust faults. The structures in the study area have accommodated approximately 6 km of shortening, accounting for 29% of the overall shortening.

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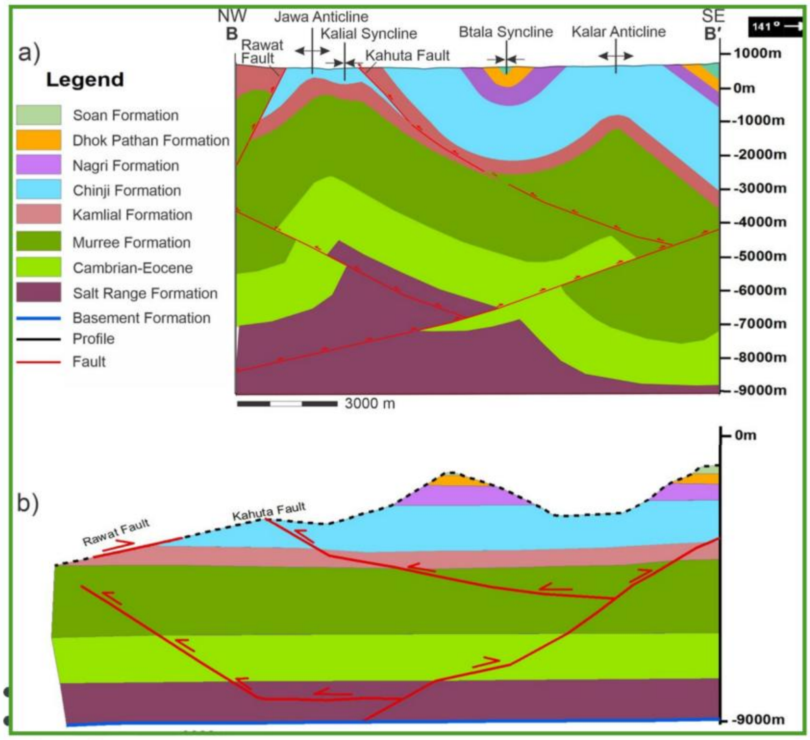

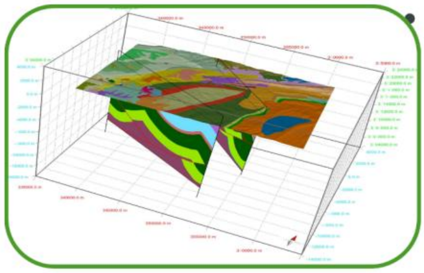

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